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Tightly Coupling Cognition: Understanding How Communication and Awareness Drive Coordination in Teams

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Tightly Coupling Cognition: Understanding How Communication and Awareness Drive Coordination in Teams

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Abstract

Modern and future visions of command and control (C2) pose new theoretical and practical issues. These adaptive, rapidly reconfigurable, and distributed organizational structures rely on developing and maintaining shared awareness between interdependent components (i.e., individuals or teams working towards shared goals). The science of teams has been an effective theoretical driver for understanding and promoting effectiveness in traditional C2. Much of this work can be leveraged in modern C2 as well; however, there are gaps in the science of teams that must be filled in order to provide science-based guidance for modern C2. This article presents a review of the science of teams and discusses how it applies to modern C2. We discuss recent theorizing on cognition and teams in order to illustrate the multifaceted ways in which cognition manifests itself during complex dynamic interaction to support coordinated teamwork. Framing this within the general rubric of team cognition we discuss how awareness propagates through teams via communication processes manifested both

implicitly and explicitly. Additionally, we discuss how team cognition supports a number of macrocognitive functions necessary for effective collaborative problem solving.

Introduction

The nature of C2 is changing. It has always been a complex endeavor, but new and asymmetric adversaries have created demands for rapid adaptation and the capacity to generate solutions to unique problems. In response to these demands, modern military organizations have been experimenting with and adopting organizational structures and technologies that enable the rapid reconfiguration of personnel and resources. Traditionally, C2 organizations have been highly structured with tight top-down control. While this configuration has many advantages (e.g., stability and reliability when the adversary's methods and strategies are relatively stable) and will not be replaced entirely, the vision for modern C2 includes organizational components designed to quickly adjust to adversaries whose tactics change on rapid time cycles.

So, change is in the wind for C2. But what scientific knowledge can be leveraged to guide the process of designing and implementing these new organizational structures? Alberts and colleagues (1999) identified three domains of research where advances must be made in order for this type of modern C2 to become plausibly effective: (1) the nature of shared awareness and the prerequisites for achieving it, (2) the nature of self-synchronization (i.e., coordination), and (3) the relationships between these two concepts. The over-arching purpose of this article is to provide an initial discussion of how these issues can be addressed by drawing upon the science of teams. This is a well established scientific tradition that has impacted traditional C2 and has much to offer modern C2 as well. However, in extending the science of teams to modern C2, it becomes apparent that there are gaps in the existing understanding of teams. The types of teams and tasks characteristic of traditional C2 are substantively different in many ways than those envisioned in modern C2. Specifi-

cally, the majority of the science to date has dealt with behavioral coordination of team member actions and not the complex cognitive tasks like planning and problem solving characteristic of the vision for modern C2.

Therefore, this article accomplishes three goals. First, we provide a review of the contributions made by the science of teams to understanding, managing, and designing for effective C2. This includes a long track record of scientific progress and practical relevance for C2. Because of their relevance to modern C2, we focus on coordination and the processes of building shared awareness. Second, we describe a set of challenges posed by modern C2. These challenges involve gaps in the present theoretical understanding of teams as well as practical implications of these gaps. Third, we describe recent efforts at extending the science of teams to support these practical considerations in modern C2. That is, efforts to better understand how teams engage in complex problem solving and planning activities can serve as a valuable theoretical driver of the design of modern C2 sociotechnical systems.

The Science of Teams in C2

The science of teams has been a critical driver in understanding performance in C2 environments for decades. In 1988, the USS Vincennes, a US Navy guided missile cruiser, mistook a commercial Iranian flight for an attacking military jet. The crew of the Vincennes fired two missiles at what they thought was an imminent threat to their safety. The immediate result of this decision by the Vincennes crew was the tragic deaths of the 290 innocent passengers and crew members aboard the Iranian flight. Although there were many contributing factors to this accident, poor communication among the Command Information Center team members on the Vincennes was one of the most significant. After this tragic failure in C2, a major research effort was launched and funded by the United States Congress, the Tactical Decision Making Under Stress (TADMUS) program, with the aim of better understanding how

decisions are made in high stress, high stakes military environments (i.e., in C2) and the role that team performance plays in the effectiveness of C2 operations (see Cannon-Bowers & Salas, 1998). The TADMUS program and other work has produced a wealth of knowledge on how teams function and subsequently how to train team members and design tools to support teamwork. In the following sections, we provide a brief review of fundamental issues in the science of teams. Of course, C2 has been influenced by other areas of research (e.g., knowledge management, organizational design, human-computer interaction, etc); however, as the present purpose is to further the understanding of how the science of teams is relevant to modern C2, and how the science of teams can be extended to better represent teams and tasks that are characteristic of modern C2, we limit the following discussion to teams. We begin with a discussion of exactly what teams are and how they are relevant to modern C2 operations. This is followed by a discussion of two critical components of the science of teams: coordination and team cognition. Team cognition is the current theoretical framework for understanding how team members build and maintain shared awareness.

Teams, Teamwork, and Team Performance in Traditional and Modern C2

A team is a set of two or more individuals interacting dynamically and adaptively through specific roles while striving towards a common and valued goal (Dyer, 1984; Salas, Dickinson, Converse, & Tannenbaum, 1992). Goal and task interdependence (Saavedra, Earley & Van Dyne, 1993) are the core defining features of a team. With the recent trends toward divergent thinking and the emphasis on complexity science in C2 research (e.g., Alberts, 2007), the question of whether or not the team is an appropriate unit of analysis in C2 becomes salient. In traditional hierarchically structured C2, boundaries are less permeable and teams are more readily identifiable as social entities. A traditional C2 team will have a significant history (i.e., the same collection of individuals will work together over extended periods of time and multiple performance episodes

or missions) as well as an explicitly identifiable structure. This may not be the case in modern C2 which is envisioned as a process of rapidly configuring a set of individuals who may be spatially or temporally distributed to address a specific problem and then disband (Letsky, Warner, Fiore, Rosen, & Salas, 2007).

The core defining features of a team (workflow interdependencies among team members, and a common set of valued goals) apply to modern C2 and therefore the significant theoretical and empirical literature concerning teams, team performance, and team cognition remain relevant. Whether the structure and composition of the team are externally imposed and clearly articulated or a problem spurs the rapid creation of a team, the science of teams is informative as both situations described involve a set of two or more interdependent individuals working toward shared and valued goals. In fact the larger C2 environment can be viewed through the teamwork lens as well. The performance of larger organizational units such as multi-team systems can be explained with the same theoretical framework applied to teams as long as the components of this larger organizational unit share a set of common goals and interact interdependently (Marks, DeChurch, Mathieu, Panzer, & Alonso, 2005). Individual team members may be working interdependently toward a proximal goal that is unique to that specific team, but for overall effectiveness a team may have to manage interdependencies with other teams while working toward more distal goals shared by the component teams of the multi-team system.

In addition to having shared goals and interdependencies, teams are often characterized as having members with unique expertise (Salas, Stagl, Burke, & Goodwin, 2007). In fact, leveraging diverse knowledge and skills is a primary impetus for forming teams to solve complex problems in modern C2. When no one individual has the requisite expertise or capacity to accomplish a goal, teams are formed. This is the both the promise and the challenge of teams in this environment—synthesizing diverse knowledge and skills. Coordination and team cognition, described in the following section,

provide a theoretical basis for understanding how this occurs, and consequently how to improve the effectiveness of these processes.

How do Teams Drive Effective C2: Coordination and Team Cognition

A major source of failure in disaster relief efforts (a task becoming more common to military organizations) stems from the fact that "people in disaster relief either have the knowledge to know what to do (because they are there, locally, in the field, but they lack the authority to decide on implementation)...or people have the authority to do it (but then lack the knowledge)" (Dekker & Suparamaniam, 2007, p. 234). Success in situations such as these involves in part connecting and, if possible, uniting, people with the power to make decisions and take action with those that have an understanding of the situation and what needs to be done. A decoupling between these two capacities is a source of inefficiency and error. Consequently, building and maintaining shared awareness is viewed as the bedrock of modern adaptive organizations. Avoiding this situation and close analogues in modern C2 involves the systematic and scientific understanding of coordination and shared awareness called for by Alberts and colleagues (1999). The fundamentals of these concepts and their interrelationships are discussed below.

Coordination

In practical terms, mission success is the gold standard by which military operations are evaluated. However, efforts at increasing mission success must necessarily address the processes of performance such as coordination that lead to the desired outcomes. A better understanding of the complexities of coordination in teams will help to clarify both the way in which shared awareness emerges from team interactions as well as how shared awareness in turn drives coordination and performance outcomes.

Fundamentally, coordination is "managing dependencies between activities" (Malone & Crowston, 1994, p. 90). In the team performance context, this involves "orchestrating the sequence and timing of interdependent actions" (Marks, Mathieu, & Zaccaro, 2001, p. 363). In dynamic environments, teams must coordinate their processes adaptively (see Burke, Stagl, Salas, Pierce, & Kendall, 2006). That is, they must change how they organize individual inputs as the demands of the situation change. There are several key behavioral processes that enable this adaptive coordination (e.g., mutual performance monitoring, back-up behavior, team leadership, communication; Salas, Sims, & Burke, 2005), but ultimately members must have a clear understanding of: 1) the situation to which they are adapting (both in terms of the external environment and internally in terms of states and capacities of their teammates); 2) the goals the team has in the present situation; and, 3) the characteristics of the team (e.g., the roles and abilities of team members, the team goals, task strategies) that can be applied to meet the changing task demands.

The type of coordination that the team engages in can be viewed as an adaptive response as well. Specifically, the capacity to shift between explicit and implicit coordination strategies is a hallmark of expert teams (Salas, Rosen, Burke, Goodwin, & Fiore, 2006). Explicit coordination relies on verbal communication (Entin & Serfaty, 1999); team members are aware of how to organize their behaviors because they are given instructions on how to do so. During implicit coordination, however, team members draw on shared mental models of the team and task to anticipate the needs of their fellow team members and pass information and other task inputs before they are requested; teams are aware of how to organize their behavior because: 1) they share an understanding of the situation; and, 2) are capable of interpreting this situation in terms of the task needs of their fellow team members. Effective teams are capable of shifting from explicit to implicit coordination strategies when workload is high (Entin & Serfaty, 1999). In this way, teams are able to reduce the 'communication overhead' (i.e., the workload associated with explicit communication processes; MacMillan, Entin, &

Serfaty, 2004) and maintain high levels of performance outcomes in stressful conditions (Adelman, Miller, & Henderson, 2003).

In sum, team coordination is how a team organizes its processes in time and can be viewed as an important product of shared awareness; that is, shared awareness enables a team to efficiently organize its behaviors and processes. This shared awareness can be developed explicitly or implicitly. However, as coordination involves interaction with the environment as well as team members interacting with each other, the processes yield important information both about the environment and team members. The act of coordinating and acting on the environment produces more information that must be integrated into individual awareness and distributed throughout the team. Therefore, the team's efforts at coordination also influence the team's shared awareness.

While coordination does not account for all of the variance in team performance outcomes (e.g., good coordination is meaningless if all of the individual task inputs are of low quality; Espinoza, Lerch, & Kraut, 2004), it is critical for leveraging the individual expertise and performance capacities of team members into performance outcomes above the levels obtainable from any one individual or the mere aggregation of individual performance outcomes (Salas, Rosen, Burke, & Goodwin, in press). In the following section, we provide an overview of team cognition, an approach to better understanding the processes involved in generating and maintaining the shared awareness that drives effective coordination.

Team Cognition

Team cognition is of practical interest because it is assumed that 'better' or 'more' team cognition is related to higher levels of performance outcomes (Cannon-Bowers & Salas, 2001). That is, the more shared understanding and awareness a team has, the better its performance processes will be and consequently, the better its outcomes will be. Conceptually, team cognition can be understood as the inter-

action of, and dependency between, intra-individual (i.e., internal cognitive) and inter-individual (i.e., external social) level processes (Fiore & Schooler, 2004). It is an emergent phenomenon in that it arises from the cognitions of individual team members as they interact with the environment (e.g., gather and interpret information) and team process behaviors (e.g., share information and coordinate action). Team cognition is analogous to cognition on the individual level (see Cooke, Salas, Kiekel, & Bell, 2004). For example, if individual cognition is conceptualized as involving cognitive structures (e.g., a semantic network that stores concepts and relations among concepts; Baddelley, 1997), it is proposed that an individual must process those structures through various mechanisms such as storage, retrieval (e.g., traversing the links in the semantic network), and mental simulation. In this light, team cognition can be understood as a process of acting on the individual level knowledge structures by the means of team interaction processes. Individual level static knowledge structures (e.g., mental models of the team, task, environment, and equipment) are called upon as the individual works to gain an understanding of the situation at hand, a process yielding a dynamic mental representation of the situation—an individual level awareness (e.g., individual situation awareness and problem representations). Subsequently, as team members interact, this individual level dynamic understanding of the situation is processed into a team level understanding via explicit and implicit communication and other team interaction processes. This interaction not only produces the shared dynamic understanding of a situation (e.g., team situation awareness, Artman, 2000; Salas, Prince, Baker, & Shrestha, 1995; team problem model, Orasanu, 1994) but long term team knowledge structures as well (e.g., shared mental models of the team, task, equipment, and environment; Cannon-Bowers, Salas, & Converse, 1993). While both the shared dynamic understanding or awareness and the shared long-term knowledge structures are held within team members (i.e., intra-individual) they are considered at the team level because the processing via team interaction produces knowledge and awareness that is no longer the product of just one person; it is specific to the team, not the individual.

In efforts to disentangle the complexities of team cognition, theoretical and empirical research has tended to fall into one of two themes (Fiore & Salas, 2004): team cognition as communication (i.e., conceptualizing communication as the cognitive processing done by a team), and team cognition as shared awareness (i.e., conceptualizing team cognition as the product of team cognitive processing). Although these two themes are complementary, it is useful to make the distinction. In the following section we introduce the macrocognition in teams perspective and subsequently we describe how team cognition, as both communication and awareness, can be used to understand the processes of building and maintaining shared awareness in complex team problem solving.

In sum, the fundamentals of the science of teams outlined above have been applied to traditional C2 to great benefit (e.g., better team training to prepare team members, better displays to facilitate shared awareness and coordination). Much of this work is directly transferable to the types of tasks envisioned for modern C2; however, there is still work to be done. In the following section, we highlight some of the new theoretical and practical issues raised by these new work arrangements and tasks. Subsequently we describe recent efforts to meet these challenges.

Theoretical Gaps and Practical Issues for Modern C2

To frame the discussion of modern C2 and illustrate salient differences with traditional C2, consider the following scenario. The Noncombatant Evacuation Operation (NEO) scenario is a simulation of a task performed by the United States Pacific Command (PACOM) and involves devising a plan for evacuating stranded humanitarian workers on an island nation overrun by rebel insurgents. This task is performed by a geographically distributed team of senior staff specialists with diverse organizational and agency backgrounds as well as differing types and levels of expertise. The team is formed ad hoc, meaning they are assembled for the sole purpose of solving this problem and do not have extensive history as

a team. Team members must gather all available information and synthesize a solution, an evacuation plan. This type of task is different in important ways from many traditional C2 operations. As complex as performance was in the CIC of the Vincennes, the team had the advantage of an extensive history of working together. Their task was relatively well defined and stable over time (e.g., the crew searched for, identified, and appropriately dealt with targets). While the existing science of teams provides much insight into how shared awareness develops and drives coordination is situations such as these, the implications for modern C2 operations such as the NEO scenario are less clear.

Modern C2 is not the only domain faced with such issues. Many work domains require rapid and adaptive responses from large numbers of individuals, teams, and larger organizational units to address dynamic and unpredictable environmental demands. These types of work domains create many challenges to effective performance and consequently pose many challenges to supporting performance in these contexts. Specifically, time pressure, information/knowledge uncertainty, dynamic information, and large quantities of information/knowledge are characteristics of the environment that exert influence on performance processes at many levels. Table 1 provides descriptions of these environmental characteristics as well as specific challenges these parameters pose for supporting modern C2. Additionally, organizational and compositional characteristics of the team create specific challenges for supporting work processes. For example, aspects of temporal and physical distribution, cultural heterogeneity, distribution of expertise and knowledge, and allocation of roles are important and difficult issues for system designers to consider.

Table 1. Situational parameters present in complex operational environments.

Situation Parameter	Description	Example Issues Posed for C2
Time pressure	time is the limiting factor on the amount of individual cognitive processing or team communication and coordination that can be devoted to task performance [50]	• How can local time constraints be communicated and represented globally in distributed environments? • How can feedback best be incorporated into displays?
Information and knowledge uncertainty	inadequate information to build an accurate or satisfactory representation of the situation or problem [33]	• How is uncertainty of information represented? • How can distributed individuals communicate uncertainty without paralinguistic content?
Dynamic information	information may become invalidated and outdated; its meaning may be altered by additional information; or it may be replaced with new information [6]	• How can the history of information best be included in designs to facilitate pattern recognition over time? • How can distributed systems communicate local interpretations?
Large amount of information	demands of an environment can out strip the cognitive resources of an individual or team [30]	• How can displays filter information and guide attention? • How can systems distribute and synthesize information across multiple users?

Building a comprehensive and coherent theory for supporting work in modern C2 requires that an understanding of the factors that emerge when individuals, teams, and teams of teams, attempt to interact over time and space to solve complex problems. In order to address this need, it has been recommended that members of the operational and analytic communities cooperate and bring to bear theory and methods from a variety of scientific disciplines, including computational and complex systems, organizational theory, and the cognitive sciences (Alberts, 2007). At present, there is no integrative theory applicable to the breadth of issues raised in this brief discussion. The science of teams has provided an initial grounding for this work, but these new team and environmental characteristics and more cognitively complex tasks require a more robust theoretical approach. In the following section, macrocognition in teams is introduced as a research area attempting to fill this void.

Extending the Science of Teams for Modern C2

Discussions of the concept *macrocognition* began due to the need to understand cognitive processes in the real world. In the field of cognitive engineering attention to cognition in naturalistic environments was the focus with the idea being that, in such settings, cognitive processes emerge in different ways when compared to laboratory settings (Cacciabue & Hollnagel, 1995; Klein at al., 2003). In this area, macrocognition was argued to pertain to "the role of cognition in realistic tasks, that is, in interacting with the environment. Macrocognition only rarely looks at phenomena that take place exclusively within the human mind or without overt interaction. It is thus more concerned with human performance under actual working conditions than with controlled experiments" (p. 57). More specifically, we focus on macrocognition in teams and this article represents an extension of some of the prior theorizing on macrocognition where the term is used to capture cognition in collaborative contexts (Warner, Letsky, & Cowen, 2005). Macrocognition in teams has been defined as "the internalized and externalized high-level mental processes employed by teams to create new knowledge during complex, one-of-a-kind, collaborative problem solving" (Letsky, Warner, Fiore, Rosen, & Salas, 2007, p. 7). In this context, higher-level mental processes are those involving the combination, aggregation, and visualization of information to support uncertainty management and building and discovering new knowledge and relationships. Internalized processes are those that occur at the individual level which are not expressed through external means (e.g., writing, speaking, gesture), while externalized processes are directly observable. A framework of macrocognition is presented in Figure 1. This framework outlines four phases of collaboration: knowledge construction, team problem solving, team consensus, and outcome evaluation and revision along with the associated macrocognitive processes (Warner, Letsky, & Cowen, 2005).

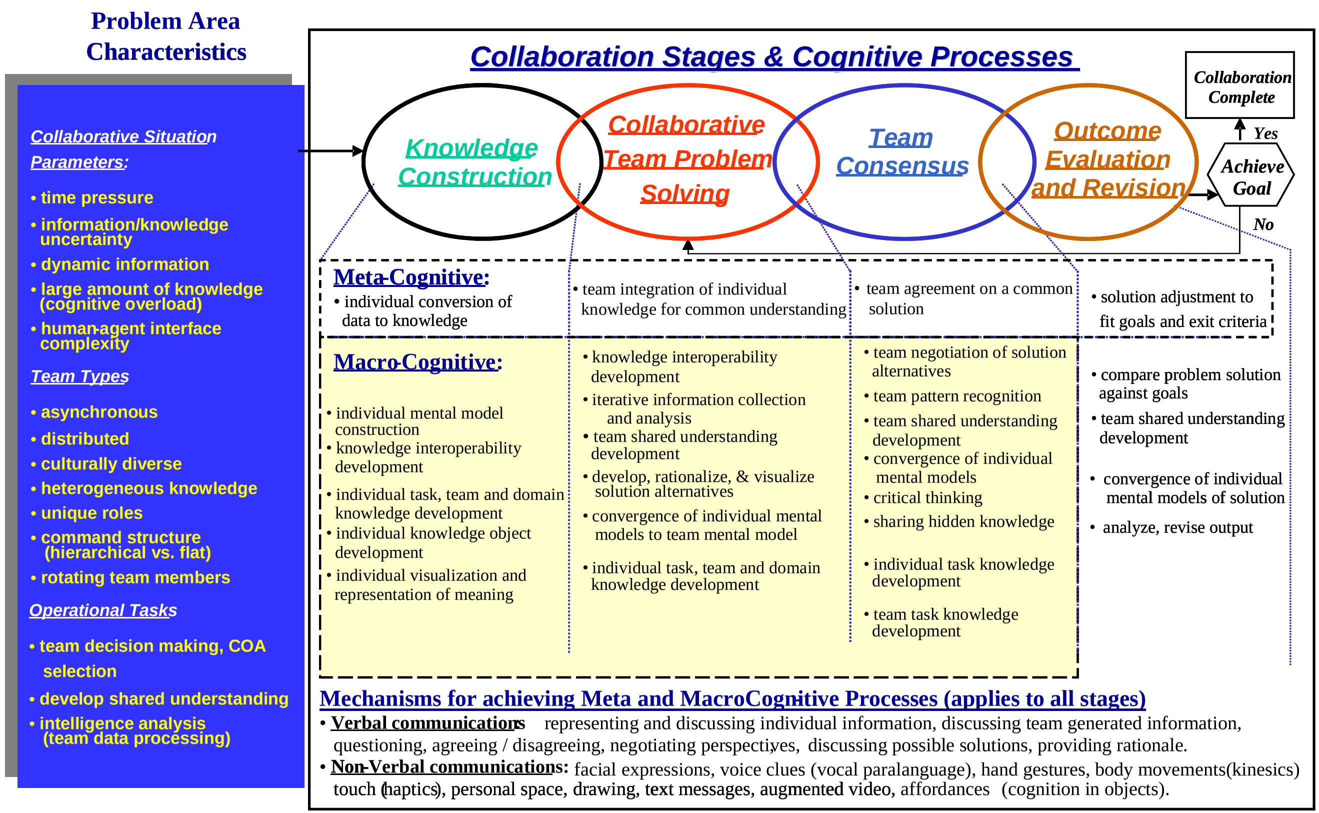

Figure 1. Framework of team collaboration: Focus on macrocognition (Warner, Letsky, & Cowen, 2005).

Although there are undoubtedly similarities between the macrocognitive and team cognition perspectives, each maintains a unique emphasis. While team cognition research and theory has emphasized behavioral coordination (i.e., the sequencing of the overt actions of team members in time; e.g., Entin & Serfaty, 1999), the macrocognitive perspective emphasizes the knowledge work done by a team. In this sense, the coordination of information inputs of individual team members is of interest. This distinction can be clarified by invoking the skills, rules and knowledge classification of human performance (Rasmussen, 1983) whereby the rule and knowledge levels are of particular interest.

Rule-based performance entails composing a sequence of task procedures that are previously known and carrying them out in a familiar environment. In the team context, this involves diagnosing the situation (which is familiar), selecting a course of action (which is routine), and coordinating the execution of the task. For example, a prototypical team engaged in rule-based performance is an aircrew that encounters an in flight problem (e.g., engine failure, unexpected weather conditions), must work to develop a shared understanding of the problem (e.g., what is the cause of the problem?), generate and choose a course of action (e.g., what procedure from a well-known set of procedures is the correct one to implement in this situation?), and carry out and evaluate the chosen course of action (e.g., team members must coordinate their individual task inputs in a relatively predefined manner to accomplish the team goal). This is the type of team performance generally investigated under the team cognition approach. However, knowledge-based performance is quite different. This involves situations that are unfamiliar, situations where there are no pre-existing rules available to guide action. Performance does not consist of selecting from a set of possible procedures or rules, but involves the generation or adaptation of rules to novel situations. This is the focus of macrocognition in teams — understanding the process by which individuals and teams generate new knowledge for addressing unique problems. In the following section we discuss how work in macrocognition can be used to better understand the types of tasks and teams that characterize mod-

ern C2 with an emphasis on shared awareness and communication as primary drivers of coordination.

How Does Shared Awareness Drive Macrocognitive Processes?

The issue of developing and maintaining shared awareness is critical in tasks more traditionally investigated under the team cognition approach and in macrocognitive tasks as well. In fact, it is perhaps a more challenging issue in macrocognitive tasks (i.e., knowledge-based performance) than in action teams (i.e., rule-based performance). Teams that are involved in continuous interaction with the environment such as action or performing teams generate more feedback for themselves. They are more tightly coupled with the environment. That is, as they coordinate their actions and perform their tasks, the effects of this performance are perceivable to them in the environment. This feedback can be used to correct the shared understanding within the team. If shared awareness is incomplete or inaccurate the effect of the team's performance may provide indicators to them that this is the case. However, in teams engaged in tasks like planning, there may be less direct interaction with the environment. This disconnect between members and the environment and in the case of distributed teams, between team members as well, poses several challenges for building and maintaining shared awareness (e.g., degradation of cue quality, feedback delays causing difficulty inferring causality, etc.; Fiore, Salas, Cuevas, & Bowers, 2003; Stagl, Salas, Rosen, Burke, Goodwin, & Johnston, 2007). In the following sections, we provide an overview of the major macrocognitive processes as hypothesized to unfold in macrocognition in teams (i.e., individual knowledge building, team knowledge building, developing a shared problem conceptualization, team consensus development, and outcome appraisal). Major macrocognitive processes are supported by multiple secondary processes at the individual and team levels. A portion of the major macrocognitive processes are visually depicted in Figure 2. Subsequently, we high-

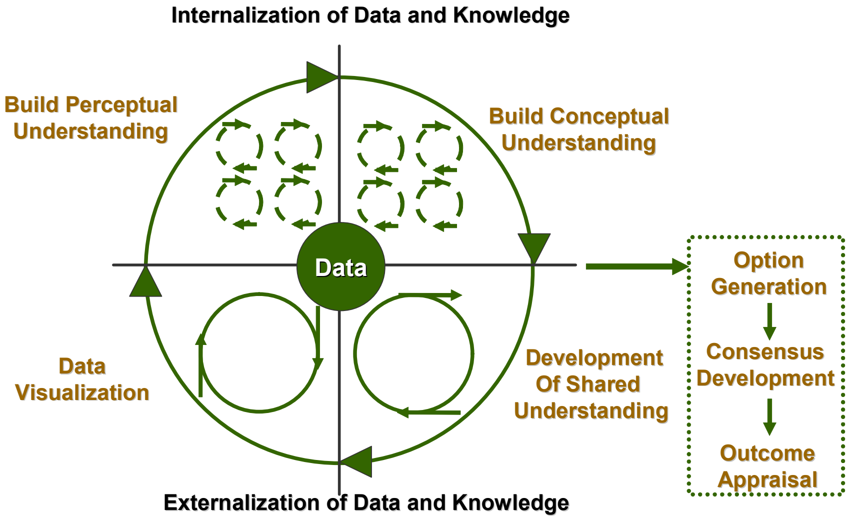

Figure 2. Overview of macrocognitive processes in team problem solving (adapted from Fiore, Rosen, Salas, Burke & Jentsch, 2007).

light the role of awareness and communication in supporting each of these processes as illustrated in Figure 3.

Individual and Team Knowledge Building

While in reality macrocognitive processes are recursive and non-sequential, the first major macrocognitive processes considered are individual and team knowledge building. Although tightly coupled, the processes of building knowledge on the individual and team levels are distinct. The core feature of these processes is a progressive refinement in the understanding of information, moving from ill-defined situations to well-defined situations (Letsky et al., 2007). Because the complexity of the macrocognitive environment is high, by definition, team members must expend large amounts of effort resolving or managing uncertainty and ambiguity. Uncertainty in such environments, where calculating probabilities of events is not practical and frequently impossible, has been defined in subjective terms as “a sense of doubt that blocks or delays action” (Lipshitz &

Strauss, 1997, p. 150). Individual team members must internalize data from the environment and reduce their uncertainty about the important elements of their environment as they work to build a conceptual understanding. As team members interact to build team knowledge, they must share elements of their individual knowledge through processes of communication and data visualization.

Communication and Awareness

In the earliest phases of collaborative problem solving, individuals must build an understanding of their environment. This is based on information that may be uniquely held by that individual or shared by the team. Additionally, each person's awareness is colored by his or her expertise (e.g., environmental cues are interpreted in light of past experience; experts may detect subtle patterns in cue configurations that novices miss, Lesgold, Rubinson, Feltovich, Glaser, Klopfer, & Wang, 1988). Therefore, communication and awareness within a team must be leveraged and we present the following research questions to help us understand this process:

1. How does critical, uniquely held information become shared?
2. How do individual interpretations of information become shared?
3. Once contradictory interpretations are shared, how do they become reconciled?

Developing a Shared Problem Conceptualization

The next major macrocognitive process involves developing a shared problem conceptualization. This involves encoding, representing, and sharing critical aspects of the problem at hand. How a problem is conceptualized or represented plays a large role in determining how that problem will be solved (Hayes, 1989). A consistent finding in many domains is that a primary mechanism of expert problem solving is building better (i.e., more accurate, more thor-

ough, more abstract) representations of a problem or situation (Chi, Feltovich, & Glaser, 1981; Zeitz, 1997). Experts know the value of a good problem representation and consequently they spend more time engaged in understanding the problem whereas novices spend more time generating possible courses of action based on lower quality problem representations (Randel, Pugh, & Reed, 1996). On the team level, building a shared problem representation involves developing overlap or congruence in individual team members' understanding of the critical aspects of the problem (Fiore & Schooler, 2004; Orasanu, 1994) including initial problem states (i.e., the current situation), goals, and operators (i.e., the resources available to the team capable of translating one problem state into another) and restrictions on the operators (Newell & Simon, 1972; Hayes, 1989).

Communication and Awareness

In this stage of macrocognition, teams must define a shared problem space (i.e., a representation of the critical aspects of the problem). In this regard, there are many empirical studies supporting the idea that group and team problem solving suffers from a convergent processing bias (Fiore, 1996; McGlynn, McGurk, Sprague Effland, Johll, & Harding, 2004); that is, groups tend to focus in on one solution or a limited set of information (e.g., the tendency to only consider shared information and not use uniquely held information; Larson, Sargis, & Bauman, 2004; Stasser et al., 1994). This is beneficial in some problem solving tasks where there is a small search space (i.e., low amounts of information have to be considered) or with highly demonstrable solutions (i.e., a problem solution is easily recognizable as an acceptable solution). However, these types of problem solving tasks are not commonplace in modern C2. Additionally, this highlights the importance of team metacognitive processes (i.e., a team's ability to monitor its own processes) in team and macrocognition (Hinsz, 2004; Hinsz, Tindale, & Vollrath, 1997). Therefore, an important area of interest for macrocognitive research is an understanding of the teamwork processes that can

counter this convergent processing bias (Rosen, Lazzara, Fiore, & Salas, 2007) and we present the following research questions to help us understand this process:

1. How do teams share information such that an adequate problem space is developed and used?
2. Given that team members may hold unique information and the significance of that information may be dependent upon information held uniquely by other team members, how can the team monitor its own shared awareness and foster divergent processing (i.e., mining the diverse expertise and information of its members) and effectively determine when to shift modes?

Team Consensus Development

In order to shift from building an understanding of the problem and its elements to generating a course of action that will move the team toward its goals, the team members must engage in the major macrocognitive process of team consensus development. This is accomplished by several processes that can be characterized as manipulating the team problem model so that the team can reach agreed upon solution options. The team works with its shared understanding of the problem, engaging in interrogation and interpretation of potential solution options until a consensus of some form is reached concerning what action the team will take. This involves both internalized processes of intuitive decision making (i.e., generating courses of action based on pattern matching, not exhaustive analytical search and reasoning) and mental simulation (i.e., evaluating a proposed course of action by internally playing it out in the current situation) as well as externalized processes of negotiation of solution alternatives and storyboarding (e.g., creating visualizations of a proposed course of action for the team).

Communication and Awareness

Awareness is critical to capitalizing on distributed expertise in the team consensus development process. From the study of expert decision making in many complex, real world domains (e.g., military, aviation, healthcare), we know the importance of an awareness of the situation or problem. Decision making in these environments is driven by pattern recognition (Klein, 1998), where the expert is able to quickly generate a course of action based on matching critical aspects of the current situation to situations that occurred in past. Therefore, better representations of problems facilitate pattern matching and the recall of relevant information. Based upon past experience, possible courses of action are recalled from past experiences (for part or all of the problem solution at hand). Given these precursors, research must help us address the following questions:

1. How do teams effectively share this proposed course of action (via verbal or representational communication)?
2. How do teams evaluate its applicability in the present context? This second step involves the team developing what can be thought of as a prospective shared awareness where they simulate how the proposed course of action will play out.

Outcome Appraisal

The final major macrocognitive process is outcome appraisal. Here the team evaluates the degree to which the selected and implemented course of action has met the team's stated goals. Depending on the context and task of the team, this may occur incrementally in which case the team may have the opportunity to re-plan, or make adjustments to the plan as it unfolds, or this may occur in a summative fashion after the plan has been implemented in full. In either case, this involves a process of receiving, interpreting, and using feedback from the environment. That is, as the environment changes due to the implementation of the plan and forces outside the control of team, information about these changes must be per-

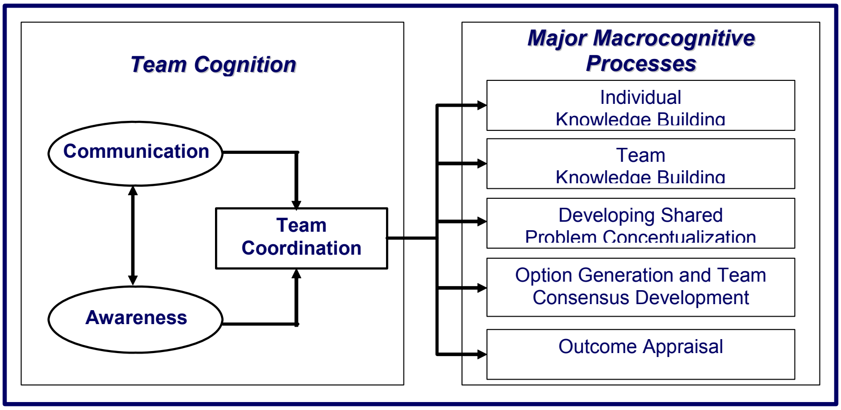

Figure 3. The role of team cognition in driving macrocognitive processes.

ceived, understood, shared within the team, and applied, either as adjustments and refinements to the plan as needed or as a learning opportunity for future performance episodes.

Communication and Awareness

In the case of teams with the opportunity to monitor the implementation of a course of action in real time, the team may adapt or, if need be, change entirely, aspects of the problem solution if feedback from the environment suggests that the plan is not going as expected and is not accomplishing its intended goal. Such adaptations are referred to as 'modifications on the fly' (Klein & Pierce, 2001) and research must help determine:

1. How do team members maintain a dynamic understanding of the environment, expectations for how the plan should unfold, goals of the situation (which form the basis of making adaptations), and contingencies developed in the team problem solving phase?
2. How does the team constantly evaluate the present situation in relation to the shared problem conceptualization and determine if critical aspects of the problem have changed?

Concluding Remarks: Challenges for Macrocognition in Teams and Modern C2

Theorizing on the nature of future C2 has emphasized the need for collaborative problem solving where a team can be rapidly assembled from disparate locations and domains of expertise to address unique problems requiring the development or adaptation of new rules of performance and the creation of new knowledge. While the performance gains promised by such organizational configurations are high so are the consequences for failure. From decades of research on teams and team or group problem solving, consistent findings have emerged: a group of individuals is not a team, and there are differences between a team of experts and an expert team (Salas et al., 2006). Individuals need to be united by interdependencies and shared goals. It is unfounded to expect high levels of performance by simply connecting individuals with collaborative tools and communication technologies. An understanding of the factors that drive effective processes in teamwork is critical for the effectiveness of modern C2.

In this article, we have argued that the scientific literature on teams offers a solid basis for understanding shared awareness and consequently major factors contributing to the effectiveness of C2. We provided an overview of the team cognition perspective on shared awareness which intrinsically links the process of building and maintaining shared awareness to the processes of team performance. Teams build shared awareness through communication (implicit and explicit); this awareness then drives team member coordination. This, in turn, creates a new situation for which the team must maintain awareness. Increases in the complexity of modern C2 are mirrored by programs of research seeking to extend the types of tasks researched from a team cognition perspective. This new area of theory development—macrocognition in teams—is young but holds promise to address the critical issues faced by modern C2 by moving beyond behavioral coordination to an emphasis on the knowledge work done by teams in complex problem solving.

While the team cognition perspective has been actively researched for some time and theoretically sound and empirically tested models have been produced, the extension into new and more complex types of tasks represented by the macrocognition perspective is far less developed. There are two central challenges to applying the construct of macrocognition in a more concrete manner. These are the interrelated challenges of theory development and metrics. While frameworks have been proposed and refined (Klein et al., 2003; Letsky et al., 2007; Warner et al., 2005), there is a need for parsimonious and empirically validated models of macrocognition. The second challenge, metrics, must be addressed in order to test models of macrocognition. Measuring performance in these macrocognitive environments is crucial to theory development, and presently there is a lack of sufficiently robust measures available. We hope that this paper stimulates further research into the theories and metrics needed to generate a robust understanding of the type of work done in modern C2 and subsequently how to best support that work and increase the performance levels reached through these types of adaptive organizational configurations.

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